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# The network stress index for power grid resilience

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ABSTRACT

This paper presents the Network Stress Index (NSI) for power grid resilience, a transition-era diagnostic instrument for cross-national assessment of electricity-network stress across 40 jurisdictions, representing approximately 87% of global electricity consumption. The NSI is a transparent, weight-adjustable composite of five normalised dimensions: integration stress, investment gap, connection-queue ratio, SAIDI reliability, and network cost share, deployed as a deposited, citable interactive dashboard. It is offered as a practical diagnostic rather than a new theoretical framework. Its main observation is that, across high-income systems, integration stress and outage duration are weakly associated, so several jurisdictions conventionally regarded as well-managed (Ireland, the Netherlands, the United Kingdom) rank among the more stressed ones once integration and queue dimensions are measured, despite low SAIDI. In contrast, the highest-SAIDI systems (South Africa, Argentina, Brazil) face a distinct, statistically distinguishable challenge rooted in generation adequacy and network underinvestment. A regression of observed SAIDI on the structural dimensions reinforces this separation: outage duration is predicted by the investment-gap dimension but not by integration stress. By making the weighting explicit and user-adjustable, the framework aims to expose rather than conceal the normative choices any composite embeds, and to support the differentiation of network-investment priorities and the allocation of grid-related climate finance.

## 1. Introduction

The global electricity system is undergoing its most consequential structural transformation since electrification. Between 2015 and 2024, the installed capacity of wind and solar photovoltaic grew from approximately 840 GW to over 3900 GW globally (International Energy Agency [1], a trajectory that embeds fundamental challenges for the networks that must integrate, balance, and transmit this generation. These challenges, curtailment, inertia loss, redispatch costs, and connection backlog are categorically different in kind from the outage-duration problems that motivated the development of conventional reliability metrics.

The System Average Interruption Duration Index (SAIDI), defined as the total customer interruption minutes divided by the total customers served [2], was designed to quantify distribution-level reliability in systems where generation was largely dispatchable and grid stability was principally a function of equipment maintenance and weather conditions. As Billinton and Allan [3] established in their foundational treatment of power systems reliability evaluation, the probabilistic indices developed in the late twentieth century were conceived for systems in which variability resided primarily in demand rather than supply. The emergence of large-scale intermittent energy sources has fundamentally altered this assumption.

Contemporary evidence indicates that SAIDI can understate the stress profile of high-renewable grids. Ireland, with a SAIDI of approximately 75 min per customer per year (Commission for Regulation of Utilities [4], would rank as “adequate” under a SAIDI-dominant assessment framework. Nevertheless, EirGrid's 2024 system performance data records 14% all-island wind dispatch-down, with 96% attributable to minimum synchronous generation requirements, a fundamental inertia constraint that SAIDI does not capture [5]. Similarly, the Netherlands reports a SAIDI of 23.9 min [6], but maintains formal grid connection moratoriums across multiple industrial zones, with TenneT's congestion management costs reaching EUR 1.6 billion in 2024. The United Kingdom records a 40-min SAIDI (National Energy System Operator [7], but hosts a connection queue of over 700 GW against approximately 110 GW of installed capacity [8].

This paper makes three contributions. First, it provides theoretical motivation for why single-dimensional reliability metrics are insufficient for cross-national grid performance assessment in the era of intermittent energy sources, and situates the framework within a comparative map of existing grid- and energy-assessment instruments

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(Section 2.1, Table 1) that sets out what each captures, what it omits, and why a new composite is warranted. Second, it presents the Network Stress Index (NSI), a rigorously sourced composite scoring framework covering 40 jurisdictions across Europe, North America, Asia-Pacific, Latin America, and the Middle East and Africa. Third, it documents the methodology in sufficient detail to enable replication, extension, and critical scrutiny, addressing the transparency deficit that Bhattacharyya and Timilsina [17] identified as endemic to energy-sector models applied in comparative policy analysis.

The NSI is deployed as an interactive research dashboard [18] within the Global Power Systems Atlas series, enabling stakeholders to adjust dimension weights and observe the sensitivity of rankings, a feature motivated by the observation of Bazilian et al. [19] that the selection of indicators and thresholds in composite energy-access metrics embeds normative choices that should be made explicit rather than concealed within an apparently objective score.

## 2. Literature review

### 2.1. A comparative map of grid-assessment instruments

Assessment instruments for electricity networks have proliferated because no single family of metrics captures every property that matters. Before reviewing each strand in detail, this subsection maps the principal instrument families against a common set of questions: what property each is built to measure, the scale at which it operates, and the transition-era stresses it structurally cannot represent. The purpose is not to rank these instruments but to locate the gap the Network Stress Index is designed to fill and, equally, to make explicit the stresses the NSI itself does not measure. Table 1 summarises the comparison; the paragraphs that follow, and Sections 2.2 to 2.7, substantiate it.

Six instrument families are relevant. Distribution-reliability indices (SAIDI, SAIFI, CAIDI) measure the duration and frequency of customer interruptions and are the operational workhorses of distribution regulation, but they are silent on generation adequacy, on the curtailment and inertia stresses of high-renewable operation, and on the forward pressure embedded in an interconnection backlog. Power-system resilience metrics characterise how a system withstands and recovers from a defined high-impact, low-probability event; they are event-centred and predominantly single-system, and are not built to compare the chronic, steady-state stresses of the transition across nations. Composite energy-policy indices, of which the World Energy Council Trilemma Index and the World Economic Forum Energy Transition Index are the most established, benchmark security, equity, sustainability and transition readiness at national scale across more than 120 countries, but they operate at the level of policy and system outcomes rather than operational network dispatch, and their security and readiness constructs load on affordability, diversification and enabling environment rather than on curtailment, redispatch or queue depth. Energy-security indices, including the fuel-supply-chain concentration measures recently applied to the nuclear fuel cycle by Haneklaus et al. [14], quantify import dependence and supplier concentration upstream of the wires; they capture a real and consequential dimension of grid security that is, however, orthogonal to the operational stresses the NSI measures. Newer transition-era stress indices [15,16] are the closest neighbours and are discussed in Section 2.6. The NSI occupies the remaining cell: a cross-national, multidimensional, operationally grounded composite of transition-era and legacy network stresses.

Two features of this map orient the rest of the review. First, the instruments differ less in quality than in what they are built to see: each is appropriately bounded in scope, and the problem addressed here is not that any of them is deficient on its own terms but that none carries the operational integration-and-queue signal at cross-national scale. Second, the map makes explicit that the NSI, too, has structural blind spots, most notably the fuel-supply-chain security dimension that energy-security indices such as Haneklaus et al. [14] foreground; Section 5.1 returns to this complementarity rather than claiming the NSI subsumes it.

### 2.2. Reliability assessment frameworks

The theoretical foundations of electricity-supply reliability assessment were consolidated by Billinton and Allan [3], whose probabilistic treatment of adequacy and security distinguishes hierarchical levels of the power system, generation adequacy, composite generation–transmission, and distribution, and argues that reliability assessment requires specifying the hierarchical scope. SAIDI, as a distribution-level metric, is appropriately bounded in scope but is sometimes applied as a proxy for total system health in contexts for which it was not designed.

Billinton and Li [20] noted that reliability indices are sensitive to the assumed load model and plant mix, cautioning against direct international comparison without harmonised definitional boundaries. This caution applies here: SAIDI definitions differ across jurisdictions, with European regulators (under EN 50160) generally excluding planned interruptions and force majeure, while many non-European utilities include planned outages, which can inflate reported figures [9]. Heylen, Deconinck, and Van Hertem [21] likewise argue that conventional

**Table 1**
Grid- and energy-assessment instrument families compared by what each captures, its scale, and what it structurally omits.

| Instrument family | What it captures | Scale | What it structurally omits | Representative sources |
|---|---|---|---|---|
| Distribution-reliability indices (SAIDI, SAIFI, CAIDI) | Duration and frequency of customer interruptions at distribution level | Utility/national | Generation adequacy; curtailment and inertia stress; connection backlog; non-harmonised definitions across jurisdictions | IEEE [2]; CEER [9] |
| Power-system resilience metrics | Ability to anticipate, withstand, adapt to and recover from a defined high-impact, low-probability event | Single-system (event-centred) | Chronic steady-state transition stress; cross-national comparability; curtailment, queue and underinvestment do not fit an onset-recovery structure | Panteli & Mancarella [10]; Panteli et al. [11]; Stankovic et al. (2023) |
| Energy-policy composite indices (WEC Trilemma; WEF ETI) | Security, equity, sustainability, and transition readiness of national energy systems | Cross-national (120+ countries) | Operational network dispatch; curtailment, redispatch and queue depth; distribution-level reliability detail | WEC [12]; WEF [13] |
| Energy-security/supply-chain concentration indices | Import dependence and supplier concentration in fuel and technology supply (incl. Nuclear fuel-cycle services) | Cross-national (supply-chain) | Everything downstream of the fuel supply: dispatch, curtailment, network reliability and investment adequacy | Haneklaus et al. [14] |
| Transition-era stress indices | Phase-structured resilience (Monie et al.); AI data-centre load vs regional capacity (Chen et al.) | Single-country/regional | Multidimensional cross-national comparison combining legacy and transition-era network stress | Monie et al. [15]; Chen et al. [16] |
| Network Stress Index (this paper) | Integration stress, investment gap, connection-queue ratio, SAIDI and network cost share in one weight-adjustable composite | Cross-national (40 jurisdictions) | Fuel-supply-chain security; single-event resilience dynamics; sub-national spatial detail | This paper |

indices, including SAIDI, are usefully complemented by indicators that capture variability and curtailment.

### 2.3. Intermittent energy sources integration and grid stress

The integration of intermittent energy sources introduces stress mechanisms with limited direct precedent in the classical reliability literature. Ela, Milligan, and Kirby [22] provided an early treatment of the associated balancing challenges, identifying operating-reserve requirements that conventional plants provide implicitly but inverter-based resources may not. At high penetration, reducing synchronous rotating mass (inertia) can create frequency-stability vulnerabilities that manifest as discrete events rather than cumulative outage minutes; Fernández-Guillámon et al. [23] review the inertia and frequency-control strategies developed in response.

Empirical evidence has accumulated for curtailment as a network-stress indicator. Bird et al. [24] analysed curtailment drivers across eleven countries and reported that elevated curtailment can coincide with low SAIDI, the configuration that motivates the integration-stress dimension of the NSI. Joos and Staffell [25] document that, for Britain and Germany, balancing and curtailment costs have risen as variable-renewable shares expanded, even as headline outage durations remained low or improved. These curtailment- and balancing-cost pressures are empirically documented rather than merely a theoretical concern.

The April 2025 Iberian blackout is the most prominent recent system event. Official investigations by Red Eléctrica de España, the Spanish government, and the ENTSO-E expert panel concluded that it resulted from a complex chain centred on voltage and reactive-power control rather than from excess renewable generation as such ([26]; ENTSO-E, 2025). The event illustrates that the operational management of voltage, reactive power, and inertia in high-renewable systems is a distinct grid-stress dimension that outage-duration metrics do not capture.

### 2.4. Power system resilience frameworks

The power-system resilience literature is the closest methodological neighbour to the present framework. Panteli and Mancarella [10] distinguish reliability, service under expected, high-probability disturbances, from resilience, the ability to anticipate, withstand, adapt to, and recover from high-impact, low-probability (HILP) events, and Panteli et al. [11] operationalise this through time-dependent metrics organised around a defined disturbance. This apparatus is event-centred rather than oriented to the chronic, steady-state stresses the NSI characterises.

The IEEE Power and Energy Society task-force synthesis [27] identifies quantifying resilience as an open problem for which no single accepted approach yet exists. Two features of this literature are relevant here. First, it concentrates on resilience to discrete extreme events, whereas curtailment, queue backlog, and underinvestment do not fit an onset–duration–recovery structure. Second, it is predominantly single-system in scope and is rarely applied cross-nationally. The NSI is therefore complementary rather than substitutive: resilience metrics assess how a system responds to a defined event, while the NSI compares cross-national systems on the chronic transition-era stresses the resilience literature has not been built to capture.

### 2.5. Composite indices in energy policy

Composite and comparative tools for cross-national energy analysis have been scrutinised at length. Bhattacharyya and Timilsina [17] find that the transparency of assumptions, data sources, and structural choices largely determines whether such tools yield credible policy guidance. This lesson transfers directly to composite indices used for comparison. Sovacool et al. [28] make the parallel case that a multidimensional condition is not adequately captured by any single metric, which is the methodological premise for combining operational (integration stress, SAIDI), structural (investment gap, queue ratio), and economic (cost share) dimensions rather than relying on outage duration alone. A recurring theme in the network-investment literature is that chronic underinvestment is frequently a governance problem, tariff suppression, institutional fragmentation, or short-termism in revenue-setting, rather than a purely technical one. Newbery et al. [29] argue that cost-reflective transmission and distribution tariffs, alongside appropriate capacity and balancing prices, are needed to align investment with both decarbonisation and reliability. The developing-world manifestation is documented by Eberhard et al. [30] for sub-Saharan Africa, and Minnaar et al. [31] provide the empirical basis for the derived South African reliability estimate used in this paper. The IEA [32] documents the global scale of the grid-investment deficit, which is visible in Argentina, South Africa, and Indonesia in the present dataset.

On connection queues, the Lawrence Berkeley National Laboratory analysis [33] documents the United States interconnection backlog and finds that only a small share of requested capacity is ultimately built, a realisation-rate caveat addressed in the methodology and country diagnostics, situating the backlog within the broader set of pressures reshaping transmission and distribution networks.

### 2.6. Recent work on transition-era grid stress

Two recent contributions sit close to the NSI in framing. Monie et al. [15] examine how the phases of the resilience process are addressed for high-renewable integrated energy systems and propose a phase-structured generic resilience index illustrated on a single country; the NSI is dimension-structured and applied at a 40-jurisdiction scale, but the shared diagnostic concern, that the transition era calls for assessment instruments different from legacy reliability and security frameworks, makes their work an important precedent.

Chen et al. [16] introduce a regional "Power Stress Index" comparing projected artificial-intelligence data-centre load with regional generation capacity; the naming proximity to the present Network Stress Index is coincidental, and the two indices were developed independently. The PSI is regional and single-ratio, whereas the NSI is cross-national and five-dimensional, so the two are best read as addressing different layers of the same phenomenon. The appearance of such indices indicates that transition-era grid stress is becoming a recognised analytical category, distinct from classical reliability and resilience.

### 2.7. Position of the network stress index within the literature

The five literature strands surveyed above, classical reliability, intermittent energy sources integration, power system resilience, composite energy-policy indices, and the recent transition-era stress literature collectively define the context for the NSI. The index does not replace any of them, nor does it claim to be a new theoretical framework: the integration–reliability divergence it foregrounds was already established empirically by Bird et al. [24] and Joos and Staffell [25], and the multidimensionality argument is well rehearsed in the composite-index literature. The contribution is instead practical and integrative. No published instrument simultaneously (a) operates at cross-national scale across 40 jurisdictions, (b) combines classical reliability with transition-era dimensions in a single composite, (c) commits to user-adjustable weighting that exposes rather than conceals the normative choices embedded in any such composite, and (d) is built on a transparent, replicable scoring rubric (Appendix A) with a deposited per-jurisdiction dataset. Each property exists individually in prior work, cross-national scale in the WEC Trilemma and WEF Energy Transition indices, transition-era integration in Monie et al. [15], weighting-transparency arguments in Bhattacharyya and Timilsina [17] and Bazilian et al. [19], but their combination, delivered as a working diagnostic tool and benchmarked in Section 5.1, is the contribution claimed in the present paper.

## 3. Methodology

### 3.1. Framework design principles

The NSI is designed around four principles derived from the literature reviewed above. First, dimensional coverage: the index must capture the distinct stress mechanisms relevant to contemporary electricity systems, including both legacy (outage duration, underinvestment) and transition-era (curtailment, inertia, queue) dimensions. Second, source transparency: every data point must be traceable to an official national regulator, transmission system operator, or authoritative analytical organisation, with sources documented per country. Third, comparability: normalisation must produce scores on a common scale despite heterogeneous underlying units (minutes, GW ratios, ordinal qualitative scores, percentages). Fourth, methodological honesty: the weighting function must be explicit and user-adjustable, acknowledging that dimension priorities are a normative choice.

### 3.2. Index formula and normalisation

The NSI is defined as a weighted linear composite of five normalised dimension scores, bounded to [0, 100]:

$$NSI = \frac{integStress}{5} \times w_1 + \frac{investGap}{5} \times w_2 + \frac{min\ queueRatio, 7}{7} \times w_3 + \frac{min\ saidi, 2000}{2000} \times w_4 + \frac{netSharePct}{55} \times w_5$$

where $w_1$ through $w_5$ are user-specified weights subject to the constraint that their sum equals 100:

$$w_1 + w_2 + w_3 + w_4 + w_5 = 100$$

The default weights are $w_1 = 45$, $w_2 = 25$, $w_3 = 15$, $w_4 = 10$, and $w_5 = 5$. The remainder of this section explains, step by step, why the formula takes this form: first, why normalisation is necessary at all, then the specific divisor chosen for each of the five dimensions and the reasoning behind it, then how the weights convert the normalised values into a single score, and finally a worked numerical example.

#### 3.2.1. Step one: why each dimension must be normalised

The five dimensions are measured in fundamentally different units. Integration stress and investment gap are ordinal scores running from 1 to 5; the connection queue ratio is a pure ratio (queued GW divided by installed GW) that can, in principle, take any non-negative value; SAIDI is measured in minutes per customer per year and ranges from low single digits to several thousand; and network cost share is a percentage. These quantities cannot be added together directly; doing so would mean adding minutes to percentages to ordinal scores, which is meaningless, and would let whichever dimension happens to be expressed in the largest numbers dominate the result purely as an artefact of its units.

Normalisation solves this by converting every dimension onto the same dimensionless 0-to-1 scale before any weighting is applied. The principle is identical in every case: each raw value is divided by the value that represents the maximum meaningful stress for that dimension. A grid with no stress on a given dimension produces a normalised value of 0; a grid at or beyond the maximum-stress value produces a normalised value of 1; everything else falls proportionally in between. The divisor is therefore not arbitrary; it is, for each dimension, the answer to the question "what raw value should count as the worst case?"

#### 3.2.2. Step two: the divisor for each dimension and its rationale

Integration stress (divide by 5). Integration stress is recorded on a five-point ordinal scale where 1 denotes minimal stress, and 5 denotes severe, systemic dispatch or stability failure. The maximum value the scale can take is 5, so dividing the raw score by 5 maps the scale onto [0, 1]: a score of 1 becomes 0.2, a score of 3 becomes 0.6, and the worst possible score of 5 becomes 1.0. The divisor is simply the top of the scale, because the scale was constructed so that 5 already represents the worst case.

Investment gap (divided by 5). The investment gap dimension uses the same five-point ordinal scale, where 1 denotes investment running ahead of need, and 5 denotes chronic underinvestment leading to structural system degradation. As with integration stress, the maximum value the scale can take is 5, so the raw score is divided by 5 to place it on [0, 1]. The two ordinal dimensions are normalised identically because they share the same scale construction.

Connection queue ratio (divide by 7, after capping at 7). Unlike the ordinal dimensions, the queue ratio has no natural upper bound; a jurisdiction could, in principle, have a queue twenty or thirty times its installed capacity. Two decisions are therefore made. First, the raw ratio is capped at 7×: any value above 7× is treated as though it were exactly 7×. This is because, beyond roughly seven times installed capacity, the queue has ceased to be a graded signal of pressure. Instead, it indicates a structural, moratorium-level constraint; the practical meaning of a 7× queue and a 15× queue is the same (the grid cannot absorb the pipeline), so the index should not treat them differently. Second, the capped value is divided by 7 so that the worst case (7× or above) maps to 1.0 and a jurisdiction with no queue maps to 0. The divisor is 7 because, after capping, 7 is the maximum value the variable can take.

SAIDI (divide by 2,000, after capping at 2000). SAIDI also has no natural ceiling and, at the extreme high end, is driven by a different phenomenon than the one the NSI is designed to measure. The raw SAIDI value is therefore capped at 2000 min: any value above 2000 is treated as 2000. The rationale is that once annual interruption duration exceeds roughly 2000 min, the cause is almost always a generation-adequacy collapse (chronic load shedding) rather than the distribution-network and integration stresses the index is built to capture; differences above that threshold are real but belong to a different diagnostic question. The capped value is then divided by 2000 so that a grid at or above the cap scores 1.0 on this dimension and a grid with near-zero outage minutes scores close to 0. The divisor is 2000 because, after capping, 2000 is the maximum value the variable can take.

Network cost share (divide by 55). Network cost share is already a percentage, so it is bounded between 0 and 100 in principle. In practice, however, no grid in the dataset comes close to 100%: the highest observed value is approximately 55%, representing grids where transmission and distribution charges make up more than half of the total consumer bill. Normalising against the theoretical maximum of 100 would compress every real observation into the bottom half of the scale, wasting the dimension's discriminating power. The raw percentage is therefore divided by 55, the approximate empirical maximum in the dataset, so that the most network-heavy grids score near 1.0 and the spread of real values uses the full [0, 1] range. This is the one dimension whose divisor is set empirically rather than by a scale maximum or a deliberate cap, and a grid above 55% would score slightly above 1.0 on this term before weighting.

#### 3.2.3. Step three: how the weights convert normalised values into a score

After Step Two, each of the five dimensions is a number between 0 and 1 (with the minor exception noted for network cost share). Each normalised value is then multiplied by its weight, $w_1$ through $w_5$, and the five products are summed. Because the weights are expressed on a 0-to-100 scale and are constrained to sum to exactly 100, each weight can be read directly as "the maximum number of points this dimension can contribute to the final score." Under the default weights, a jurisdiction at maximum stress on integration (normalised value 1.0) contributes the full 45 points from that dimension; a jurisdiction at half the maximum (normalised value 0.5) contributes 22.5 points; a jurisdiction with no integration stress contributes 0. The same logic applies to the other four dimensions, each with a weight of 25, 15, 10, and 5.

This is why the index is bounded to [0, 100]. Each normalised term lies in [0, 1], so the maximum any single term can contribute is its own weight; and since the weights sum to 100, all five terms together can contribute 100. A hypothetical jurisdiction at maximum stress on every dimension would score exactly 100; a hypothetical jurisdiction with zero stress everywhere would score exactly 0. Real jurisdictions fall in between. The weights are the only part of the formula the user changes: adjusting them redistributes the number of points each dimension can contribute, but as long as they continue to sum to 100, the [0, 100] bound is preserved. Table 2 summarises the normalisation rule for each dimension (see Table 3).

### 3.2.4. Step four: A worked example

To make the procedure concrete, consider a hypothetical jurisdiction with the following raw values: integration stress score of 4 (out of 5); investment gap score of 2 (out of 5); a connection queue ratio of 3.5×; a SAIDI of 500 min; and a network cost share of 22%. Applying the default weights, the calculation proceeds in two stages.

First, normalise each dimension. Integration stress: $4 \div 5 = 0.80$. Investment gap: $2 \div 5 = 0.40$. Queue ratio: 3.5 is below the cap of 7, so $3.5 \div 7 = 0.50$. SAIDI: 500 is below the cap of 2,000, so $500 \div 2000 = 0.25$. Network cost share: $22 \div 55 = 0.40$.

Second, multiply each normalised value by its weight and sum the results: $(0.80 \times 45) + (0.40 \times 25) + (0.50 \times 15) + (0.25 \times 10) + (0.40 \times 5) = 36.0 + 10.0 + 7.5 + 2.5 + 2.0 = 58.0$. The jurisdiction's NSI score is therefore 58.0, which places it in the stressed tier (48–65). The example also illustrates how the weighting shapes the result: integration stress contributes 36 of the 58 points, not because its raw score was the highest but because its 45-point weight, combined with a high normalised value of 0.80, gives it by far the largest share of the total.

**Table 2**
Normalisation rule and divisor rationale for each NSI dimension.

| Dimension | Raw unit | Divisor | Why this divisor |
|---|---|---|---|
| **Integration stress** | Ordinal score 1–5 | 5 | 5 is the top of the ordinal scale and corresponds to the worst case (severe, systemic failure), so dividing by 5 maps the scale to [0, 1]. |
| **Investment gap** | Ordinal score 1–5 | 5 | Same five-point scale construction as integration stress; 5 denotes chronic underinvestment, the worst case, so the divisor is again the scale maximum. |
| **Connection queue ratio** | Ratio (queue GW/installed GW) | 7 (after capping at 7) | The ratio is unbounded, so it is first capped at 7×, beyond which a queue signals a structural moratorium rather than a graded pressure, then divided by 7 to yield the post-cap maximum. |
| **SAIDI reliability** | Minutes per customer per year | 2000 (after capping at 2000) | SAIDI is unbounded and, above ~2000 min, is driven by generation-adequacy collapse rather than network stress; it is capped at 2,000, then divided by 2000 to yield the post-cap maximum. |
| **Network cost share** | Percentage of the total consumer bill | 55 | Although a percentage can reach 100, the empirical maximum in the dataset is ~55%; dividing by 55 rather than 100 uses the full [0, 1] range instead of compressing real values into the bottom half. |

**Table 3**
NSI tier classification and country distribution.

| Tier | NSI Range | Characterisation | Countries in the Dataset |
|---|---|---|---|
| **Crisis** | > 65 | Structural failure or chronic underfunding: the grid cannot simultaneously meet reliability and transition demands | Brazil, United Kingdom, Ireland, Australia |
| **Stressed** | 48 – 65 | Under significant pressure, active integration problems or investment gap, transition risks materialising | United States, Netherlands, Spain, Chile, Germany, South Africa, Greece, India, New Zealand, Poland, Mexico, China, Italy, Türkiye |
| **Pressured** | 32 – 48 | Manageable stress with material forward challenges; some dimensions under strain | Morocco, Indonesia, Argentina, Egypt, Saudi Arabia, Japan, Colombia, Sweden, Portugal, Denmark, Belgium, Thailand |
| **Adequate** | 18 – 32 | Performing with forward challenges; investment is currently broadly sufficient. | Czech Republic, Austria, South Korea, France, Canada, Finland, Norway |
| **Good** | < 18 | Well-funded and operationally resilient; low integration and reliability stress | Switzerland, United Arab Emirates, Singapore |

## 3.3. Dimension definitions and data sources

### 3.3.1. Integration stress (default weight: 45%)

Integration stress captures the operational and stability challenges of integrating variable renewable energy. It is scored on a five-point ordinal scale (full rubric in Appendix A) based on three interacting observables: renewable curtailment rates published by national system operators; redispatch and constraint costs reported in regulatory determinations; and documented frequency or inertia-stability incidents. Primary data for these observables are drawn from system-operator and regulator publications and are listed by jurisdiction in Supplementary S1. The emphasis on curtailment and balancing cost is consistent with the system-flexibility literature [34]. Where flexibility resources are structurally absent, the same renewable share tends to produce higher curtailment and redispatch costs, and thus a higher integration-stress score.

Primary data sources for curtailment include: Bundesnetzagentur [35] for Germany (renewable curtailment equal to 3.5% of renewable generation, with total grid congestion management costs of approximately EUR 2.8 billion in 2024); NESO [7] for the United Kingdom (constraint costs of GBP 1.46 billion); EirGrid [5] for Ireland (14% all-island wind dispatch-down, 96% attributable to synchronous inertia constraints); AEMO [36] for Australia (7.2 TWh curtailed in the National Electricity Market, a 67% year-on-year increase); National Energy Administration [37] for China (4.1% wind curtailment, 3.2% solar curtailment nationally, with regional maxima exceeding 30% in Tibet); and the Inter-American Development Bank [38] for Latin American markets (Chile: 18.7% curtailment in Q1 2024; Brazil: 10–17% curtailment in late 2024). European aggregate estimates from Aurora Energy Research [39] place continental curtailment costs at EUR 8.9 billion in 2024, with 72 TWh curtailed across EU member states.

The selection of 45% as the default weight for integration stress reflects two considerations. First, the empirical evidence from Bird et al. [24], EirGrid [5], AEMO [36], and the official analyses of the April 2025 Iberian event demonstrate that integration stress, not outage duration, is the primary binding constraint on network performance in the 15–25 jurisdictions with intermittent energy sources shares exceeding 30%. Second, the index is explicitly designed for the energy transition context; a SAIDI-dominant weighting would be appropriate for a legacy grid assessment tool, but would systematically misrepresent the stress profile of high-renewable systems.

### 3.3.2. Investment gap (default weight: 25%)

The investment gap dimension assesses whether capital investment in transmission and distribution infrastructure is keeping pace with demand growth and the energy transition. It is scored on a five-point ordinal scale: 1 (excellent: investment ahead of identified need); 2 (good: broadly adequate); 3 (moderate: gaps evident but manageable); 4 (strained: significant underinvestment); 5 (crisis: chronic underinvestment creating structural system degradation). Scores are derived from a consensus synthesis of national TSO ten-year network development plans, national regulatory determinations (including multi-year price controls and revenue allowances), IEA country energy policy reviews, and independent assessments from organisations including Wood Mackenzie and S&P Global Commodity Insights.

The investment gap dimension captures a dynamic documented across the dataset: chronic underinvestment is, in many jurisdictions, primarily a political economy problem rather than a technical or financial one, driven by tariff suppression (Argentina, Egypt), institutional fragmentation (USA, India), and state utility insolvency (South Africa, Indonesia). This dimension, therefore, serves as a leading indicator of future reliability deterioration in jurisdictions where current SAIDI figures may not yet reflect the consequences of sustained underinvestment.

### 3.3.3. Connection queue ratio (default weight: 15%)

The connection queue ratio is defined as the total GW of generation, storage, and demand-side resource projects with active grid connection applications (queue GW) divided by the total installed generation capacity (GW). This ratio measures the backlog of projects awaiting interconnection, a forward-looking indicator of network congestion and the pace of the energy transition relative to grid hosting capacity.

Data sources include: NESO [8] for the UK (approximately 700 GW in queue against roughly 110 GW installed, ratio 6.4×); Lawrence Berkeley National Laboratory [33] for the USA (approximately 2600 GW of generation and storage in interconnection queues as of the end of 2023, against an installed fleet of roughly 1300 GW, ratio of about 2.0×); AEMO [40] for Australia (approximately 55 GW against 55 GW installed, ratio 1.0×); and national TSO publications for European jurisdictions (RTE for France, TenneT for Germany and Netherlands, EirGrid for Ireland).

An important methodological caveat concerns realisation rates. LBNL [33] documents that only a small share of the capacity entering the United States interconnection queues, on the order of 14% of capacity from the 2000–2018 cohort, is ultimately built, the remainder being withdrawn before commercial operation. The queue ratio, therefore, overstates near-term connection pressure to varying degrees, depending on market maturity and application screening rigour. The NESO [8] reform process for the UK queue introduced cluster-based studies designed to filter speculative applications; the post-reform active pipeline is materially smaller than the headline figure, though still substantially larger than near-term hosting capacity. This caveat is incorporated in the country diagnostic texts for affected jurisdictions.

### 3.3.4. SAIDI reliability (default weight: 10%)

SAIDI (System Average Interruption Duration Index) is defined by IEEE Standard 1366 (2012) as the sum of customer interruption minutes divided by the total number of customers served, measured over a calendar year. Data are sourced directly from national regulatory annual publications: Ofgem for the UK, Bundesnetzagentur for Germany, CRE for France, CNMC for Spain, Netbeheer Nederland, ERU for Czechia, CREG for Belgium, and equivalent bodies for all 40 jurisdictions.

The SAIDI dimension receives the lowest default weight (10%) for three reasons established in the preceding literature review. First, SAIDI definitions are not internationally harmonised: European EN 50160 regulators generally exclude planned interruptions and force majeure; Japan's OCCTO and many developing-world operators include planned outages; and some utilities apply IEEE Major Event Day (MED) exclusions while others report all-in figures [9]. Second, as demonstrated empirically in the results section, low or average SAIDI is frequently accompanied by more acute integration challenges, so that a high SAIDI weight can underweight the most transition-relevant stresses. Third, for high-SAIDI jurisdictions (South Africa at 4500 min/year, Brazil at 1200 min/year, Indonesia at 800 min/year), the driving factor is generation adequacy, a structurally different problem from either intermittent energy sources integration or network underinvestment, and one better captured by the investment gap dimension.

It is worth stating plainly why a metric the paper criticises is nonetheless retained as one of the five dimensions, since the two positions can appear to be in tension. SAIDI is included in a specific and limited role: as a legacy reliability baseline and as the empirical counterpoint against which integration stress is measured. It is not retained as a general proxy for system health, which is precisely the use the paper argues against. The critique in this paper is directed at SAIDI-dominant assessment, in which outage duration is treated as the primary or sole indicator of grid performance, not at SAIDI as such, which remains the best-established, most widely reported measure of realised distribution reliability. Retaining it serves three functions. First, it anchors the composite in an outcome that regulators actually report and stakeholders recognise, preventing the index from becoming a purely forward-looking or qualitative construct. Second, it is analytically indispensable to the central finding: the near-orthogonality of integration stress and SAIDI (Section 4.4.1) can only be demonstrated, and the two crisis types only distinguished, if SAIDI is present in the framework as the reliability axis against which the integration axis is contrasted. Removing SAIDI would not strengthen the argument; it would make the argument impossible to state. Third, its low default weight (10%) encodes the paper's substantive claim, that in the transition era realised outage duration is one input among several rather than the master indicator, while the user-adjustable reliability-first preset (SAIDI 45%) lets any analyst who disagrees restore it to primacy and observe the consequences directly. SAIDI is thus best read as the adequacy-and-legacy baseline of the composite: retained for what it genuinely measures, weighted for what it cannot.

For South Africa, the SAIDI figure of approximately 4500 min per customer per year is not an officially reported SAIDI value but an estimate derived by the author from the 2023 load-shedding record. Eskom's reported distribution reliability indices capture network faults only and exclude national load shedding, so a load-shedding-inclusive figure must be derived. The inputs are drawn from open official sources: approximately 6950 h of load shedding and on the order of 16,000 GWh of energy shed in 2023, against an Eskom fleet energy-availability factor of about 55%, as recorded through the Eskom Data Portal and the Eskom Integrated Report 2023 and synthesised by the CSIR [41], with the underlying series compiled by EskomSePush [42] and The Outlier. Converting national load shedding into customer-minutes is method-sensitive: a conservative rotational allocation of the load-shedding hours yields roughly 4000–5000 customer-minutes per year, whereas a load-weighted energy-not-served calculation, in which the approximately 16,000 GWh shed represents about 7–8% of national supply, implies a substantially higher figure. Crucially, every one of these derivations lies above the 2000-min SAIDI normalisation cap, so South Africa saturates the SAIDI dimension at 1.0 regardless of which estimate is used, and its NSI score and ranking are invariant to the precise value; the uncapped-SAIDI sensitivity variant (Table 5) confirms this directly. The derivation and its sensitivity to the rotational assumption are discussed further in the limitations section. For the USA, the figure of 367 min is taken directly from EIA Form 861 [12], representing the 2023 national mean, including major event days; excluding major event days, the equivalent figure is 124 min.

#### *3.3.5. Network cost share (default weight: 5%)*

Network cost share is defined as transmission and distribution charges (T-NUoS and D-UoS, in USD/MWh) expressed as a proportion of the Total Energy System Consumer Cost (TESCC), the comprehensive consumer electricity cost metric developed in Küfeoğlu [43] in Global Power Systems Atlas Volume VII. This dimension provides a revealed economic measure of the overhead burden the network imposes on consumers.

The dimension is assigned a small anchor weight (5%) because it is ambiguous in sign: high cost share can reflect heavy investment in network infrastructure efficiently recovered through tariffs (Germany, UK), or structural inefficiency or market power. The dimension is retained rather than excluded because it provides an empirical anchor for the qualitative investment gap score and enables cross-referencing with the full TESCC dataset.

### *3.4. Tier classification*

NSI scores are assigned to five operational tiers based on theoretically motivated thresholds.

### *3.5. Geographic and jurisdictional coverage*

The NSI covers 40 jurisdictions selected to provide broad geographic coverage, economic diversity, and representation of major grid archetypes, high-renewable export markets (Norway, Brazil), rapidly transitioning markets (UK, Germany, Ireland, Australia), large emerging economies (India, China, Indonesia), hydropower-dominant systems (Canada, Colombia), and Gulf state modern grids (UAE, Saudi Arabia). Together, the 40 jurisdictions represent approximately 87% of global electricity consumption. Coverage is limited by data availability: jurisdictions without publicly accessible national SAIDI reporting, official TSO connection queue publications, or regulator-filed investment plans were excluded.

### *3.6. Sensitivity analysis: weight presets*

To address the concern raised by Bhattacharyya and Timilsina [17] and Bazilian et al. [19] about normative opacity in analytical instruments used for policy, four weight configurations are pre-defined and available in the interactive dashboard (Table 4).

### *3.7. Normalisation-sensitivity analysis*

To test whether the normalisation caps are outcome-determining, the full ranking was recomputed under ±20% perturbations and fully uncapped variants of each cap (Table 5). Each cap is justified on a stated principle: the queue ratio is capped at 7× because beyond that level the queue signals a structural, moratorium-level constraint rather than graded pressure (consistent with the low realisation rates documented by Ref. [33]); SAIDI is capped at 2000 min because above that level interruption duration reflects generation-adequacy collapse, a phenomenon the investment-gap dimension is better suited to capture; and the cost-share divisor (55%) is the empirical maximum, entering through a strictly monotone linear transform on the lowest-weighted term and therefore unable to reorder jurisdictions.

**Table 5**
Sensitivity of the ranking to normalisation caps and divisors (N = 40).

| Normalisation variant | Spearman vs default | Tier reclassifications |
|---|---|---|
| Queue cap 5.6 (−20%) | 0.9991 | 2 |
| Queue cap 8.4 (+20%) | 0.9992 | 1 |
| Queue uncapped | 0.9992 | 2 |
| SAIDI cap 1600 (−20%) | 0.9979 | 1 |
| SAIDI cap 2400 (+20%) | 0.9996 | 0 |
| SAIDI uncapped | 0.9981 | 1 |
| Cost-share divisor 44 (−20%) | 0.9998 | 4 |
| Cost-share divisor 66 (+20%) | 0.9994 | 4 |

Rankings are essentially invariant to every cap choice: the Spearman correlation between each perturbed ranking and the default ranking never falls below 0.998, and tier reclassifications never exceed four of forty. Notably, uncapping SAIDI, the variant most relevant to high-SAIDI developing-world cases, changes the ranking negligibly because those jurisdictions' stress is already carried by their investment-gap scores. The caps shape the interpretation of individual dimensions but do not drive the cross-national result; an uncapped-SAIDI column is provided in Supplementary S1.

## 4. Results

### *4.1. Descriptive statistics*

Across the 40 jurisdictions, the mean NSI score under default weights is 44.3 (standard deviation approximately 16.4), reflecting a dataset that spans from near-optimal grid performance (Singapore: 15.8; UAE: 16.3; Switzerland: 17.4) to severe structural crisis (Brazil: 76.9). Four countries are classified in the crisis tier, fourteen in stressed, twelve in pressured, seven in adequate, and three in good, a distribution skewed toward higher stress levels consistent with the global grid infrastructure investment deficit documented by IEA [32].

Integration stress scores have a mean of 2.70 out of 5.0, with five countries receiving the maximum score (Spain, Ireland, Australia, Brazil, Chile). Investment gap scores have a mean of 2.78 out of 5.0, with several countries rated at the crisis level (Argentina, South Africa) or severely strained (India, Indonesia, USA, Mexico). Queue ratios range from 0.0 (Singapore, which has no grid-connected renewable projects in queue) to 6.4× (UK). SAIDI values span from 2 min (Singapore, UAE) to approximately 4500 min (South Africa, on the derived estimate described in Section 3.3.4), with a mean of 327 min.

### *4.2. Key cross-national findings*

#### *4.2.1. The integration-reliability divergence*

A central empirical finding of the NSI is the divergence between integration stress and SAIDI across the developed-world subsample. The five countries with the most severe integration stress scores (5/5), Spain,

**Table 4**
NSI weight presets for sensitivity analysis.

| Preset | Integration Stress | Investment Gap | Queue Ratio | SAIDI | Cost Share | Analytical Rationale |
|---|---|---|---|---|---|---|
| **Default** | 45% | 25% | 15% | 10% | 5% | Transition-era priority: intermittent energy sources integration is the primary binding constraint for most developed-world grids |
| **Transition-First** | 55% | 20% | 20% | 5% | 0% | Maximum emphasis on intermittent energy sources integration and connection backlog; appropriate for high-ambition renewable policy contexts |
| **Reliability-First** | 20% | 20% | 10% | 45% | 5% | Legacy grid framing; SAIDI-dominant; appropriate for development bank contexts prioritising access and outage reduction |
| **Equal Weights** | 20% | 20% | 20% | 20% | 20% | Agnostic baseline; treats all dimensions as equivalent; useful for initial screening. |

Ireland, Australia, Brazil, and Chile, have a mean SAIDI of 348 min, substantially elevated by Brazil (1200 min) and Australia (250 min). Excluding these two, the mean SAIDI for the three highest-income countries integrating intermittent energy sources (Spain, Ireland, Chile) is approximately 97 min, lower than that of the US, Poland, or Sweden. Ireland, at SAIDI 75 min, would rank among the top-15 most reliable grids in the dataset under a SAIDI-only assessment, yet ranks third-most stressed under the NSI default configuration, primarily on account of its 14% wind dispatch-down rate and the fundamental synchronous inertia constraint that EirGrid [5] has identified as the defining system challenge.

This divergence is consistent with the framework's premise that SAIDI and integration stress measure different grid properties (quantified in Section 4.4.1: Spearman $\rho = 0.18$, not significant), and high reliability is not merely compatible with high integration stress but is frequently coincident with it, because the countries most advanced in intermittent energy sources deployment are also those with the most extensive operational experience with integration challenges.

#### 4.2.2. The connection queue crisis

The connection queue data reveal a bifurcated picture between markets with active queue crises and those where the queue is not yet a binding constraint. The UK's 6.4× queue ratio is the most extreme in the dataset and reflects a decade of constrained permitting and limited transmission build-out. The structural consequence of proximity to offshore wind resources is that the majority of queued projects are offshore, targeting a grid that has not kept pace with the ambition of the renewable pipeline [8]. Greece (3.0×), Ireland (2.3×), and Spain (2.0×) also exhibit ratios exceeding 2×, in each case reflecting a large solar and wind development pipeline against grids that face either geographic barriers (Greece's island systems) or operational constraints (Ireland's inertia ceiling, Spain's post-blackout transmission prioritisation).

The USA is distinctive in that it has a queue. At the same time, not the highest ratio, it represents the largest absolute backlog of any single market in the world: LBNL [33] reports approximately 2600 GW of generation and storage capacity in interconnection queues as of the end of 2023, more than twice the installed U.S. fleet. LBNL [33] documents that average interconnection study durations have lengthened from under two years for projects built in 2000–2007 to roughly five years for projects built in 2023, effectively serialising a development pipeline that requires parallel processing. FERC Order 2023 (2023), introduced to reform interconnection queue processes, is anticipated to improve throughput, but its effects were not yet visible in the 2023–2024 data used in this study.

#### 4.2.3. Structurally different crises: High-SAIDI developing-world grids

South Africa (NSI 57.1, SAIDI ~4500 min, derived; see §3.3.4), Brazil (NSI 76.9, SAIDI 1200 min), Argentina (NSI 42.9, SAIDI 1100 min), and Indonesia (NSI 45.9, SAIDI 800 min) present a structurally different challenge from the intermittent energy sources integration crisis visible in the developed-world top-10. In each case, the primary driver is generation adequacy or distribution infrastructure collapse, rather than dispatch problems with intermittent energy sources. South Africa's 2023 load shedding peak of approximately 6950 cumulative hours [42] reflects Eskom's coal fleet Energy Availability Factor falling to roughly 55% over the calendar year, not renewable intermittency. Brazil's SAIDI reflects chronic underinvestment in the distribution network across the ANEEL-regulated network, rather than in wind or solar integration [44]. Argentina's 1100 min SAIDI is a direct consequence of politically suppressed electricity tariffs that have produced nominal distribution company revenues inadequate to fund maintenance and capital expenditure [45].

The NSI correctly classifies these as high-stress jurisdictions, but for reasons different from those of the intermittent energy sources-stress cluster. This distinction is critical for policy: the interventions required in South Africa (Eskom fleet rehabilitation, distribution maintenance investment, tariff normalisation) are categorically different from those required in Ireland (grid-forming inverters, synchronous condensers, System Non-Synchronous Penetration (SNSP) limit increase) or the UK (transmission build-out, queue reform).

### 4.3. Sensitivity of rankings to weight choice

Switching from the default weight configuration to the Reliability-First preset produces the most dramatic ranking changes in the dataset. Under Reliability-First weights (SAIDI 45%), Ireland falls from the 3rd-most stressed to 10th, the Netherlands from 6th to 13th, and the UK from 2nd to 9th, while South Africa, Brazil, Argentina, and Indonesia rise substantially. Conversely, switching to the Transition-First preset (integration stress 55%, queue 20%) accentuates the crisis classification of Ireland, Australia, and Spain. It demotes South Africa and Argentina (low integration stress scores of 1/5 and 2/5, respectively) toward the pressured tier.

This sensitivity analysis, directly accessible in the interactive dashboard, demonstrates the normative dimension of grid health assessment and validates the concern articulated by Sovacool et al. [28] that single-metric frameworks inevitably provide an incomplete and possibly misleading assessment. The NSI makes these choices transparent and user-modifiable.

### 4.4. Statistical structure and uncertainty

#### 4.4.1. Correlation structure

Spearman rank correlations among the five dimensions and the composite (Table 6) substantiate the central claim and reveal two coherent stress clusters. Integration stress and SAIDI are statistically decoupled ($\rho = 0.18$, $p = 0.27$): the divergence is real, not anecdotal. By contrast, investment gap and SAIDI correlate strongly ($\rho = 0.72$, $p < 0.001$), forming an adequacy cluster, while integration stress and the queue ratio form a transition-stress cluster ($\rho = 0.73$, $p < 0.001$). The two clusters are the statistical signature of the two crisis types the paper distinguishes.

#### 4.4.2. Principal component analysis

PCA on the five standardised dimensions requires all five components to span the data; no dimension is redundant. PC1 (42.2% of variance) is a general transition-stress axis loading on queue, integration, cost, and investment; PC2 (28.9%) is an adequacy axis loading on SAIDI and investment gap. The first two components capture 71.1% of the variance, and the first three components capture 84.2% (Table 7). The two-axis structure provides independent statistical confirmation that integration stress and adequacy stress are distinct phenomena and justifies retaining all five dimensions rather than collapsing them.

#### 4.4.3. Inter-rater reliability and Monte Carlo uncertainty

**Inter-rater reliability.** A second rater independently re-applied the published rubric (Appendix A) to the documented evidence for the twelve worked-example jurisdictions. Exact agreement was 91.7% (11 of 12), agreement within one band was 100%, and the linear- and quadratic-weighted Cohen's κ were 0.94 and 0.98, respectively; the sole discrepancy (Ireland integration stress, 5 vs 4) falls on the band-4/5

**Table 6**
Spearman correlations ($n = 40$). IS integration stress; IG investment gap; Q queue ratio; CS cost share.

| | IS | IG | Q | SAIDI | CS | NSI |
|---|---|---|---|---|---|---|
| IS | 1.00 | 0.37 | 0.73 | 0.18 | 0.33 | 0.90 |
| IG | 0.37 | 1.00 | 0.46 | 0.72 | 0.28 | 0.68 |
| Q | 0.73 | 0.46 | 1.00 | 0.30 | 0.38 | 0.80 |
| SAIDI | 0.18 | 0.72 | 0.30 | 1.00 | −0.15 | 0.42 |
| CS | 0.33 | 0.28 | 0.38 | −0.15 | 1.00 | 0.39 |
| NSI | 0.90 | 0.68 | 0.80 | 0.42 | 0.39 | 1.00 |

**Table 7**
PCA explained variance and leading loadings.

| Component | Variance | Cumulative | Dominant loadings |
|---|---|---|---|
| PC1 | 42.2% | 42.2% | queue (0.53), integration (0.51), cost (0.48), investment (0.46) |
| PC2 | 28.9% | 71.1% | SAIDI (0.75), investment (0.52) |
| PC3 | 13.1% | 84.2% | cost (0.77), integration (−0.60) |
| PC4/PC5 | 9.7%/ 6.2% | 100% | residual |

boundary the rubric itself flags. Full details are reported in Appendix A.4.

**Monte Carlo on the weights.** Drawing 20,000 wt vectors from a Dirichlet distribution centred on the defaults, the mean Spearman correlation between a random-weight ranking and the default ranking is 0.98 (5th percentile 0.95), and the median across-jurisdiction rank standard deviation is 1.38 positions. The most weight-sensitive jurisdictions are South Africa and Argentina, the adequacy-crisis cases whose classification depends on whether SAIDI or integration is privileged, thereby quantifying the argument that the normative weighting choice matters most for cases distinguishing the two crisis types.

**Monte Carlo on the ordinal scores.** Independently perturbing every 1–5 score by ±1 band (20,000 draws) retains top-10 membership in 76.6% of draws; per-jurisdiction tier-change probabilities identify boundary-sensitive cases (Netherlands, Australia, Ireland near 0.36) and essentially fixed cases (the crisis and good tiers).

#### 4.4.4. Construct validity

Integration stress is uncorrelated with raw renewable share ($\rho = 0.11$, not significant), confirming that it measures a grid's absorption capacity, inertia, flexibility, and transmission headroom, rather than penetration alone, and explaining why neither a renewable-share metric nor SAIDI can substitute for it. An outcome regression on the present cross-section is reported in Section 4.4.5; predictive validation against realised future outcomes (curtailment cost, capex delivery, forward reliability) requires a longitudinal panel and is identified as future work (Section 5.6).

#### 4.4.5. Outcome regression

To test whether the framework's structural dimensions correspond to an independently observed outcome, regulator-reported SAIDI (log-transformed) was regressed on the four non-reliability dimensions and renewable share across the 40 jurisdictions (Table 8). The model accounts for a substantial share of the variation in observed outage duration ($R^2 = 0.68$). The investment-gap dimension is the dominant predictor (standardised $\beta = 0.84$, $p < 0.001$). In contrast, integration stress ($\beta = 0.06$, $p = 0.60$), the queue ratio ($\beta = -0.01$, $p = 0.91$), and renewable share ($\beta = 0.14$, $p = 0.16$) are not statistically associated with observed outages; network cost share carries a modest negative coefficient ($\beta = -0.33$, $p = 0.005$), consistent with better-funded networks recovering higher tariffs while maintaining lower outage durations. The result indicates that observed reliability tracks the adequacy dimension rather than the integration dimension, consistent with the two-crisis-types interpretation: integration-stressed grids do not, in general, show elevated outage duration. This is a cross-sectional construct-validity test; predictive validation against realised future outcomes is identified as future work (Section 5.6).

**Table 8**
Regression of observed SAIDI ($\log_{10}$) on structural dimensions; standardised coefficients, $n = 40$, $R^2 = 0.68$.

| Predictor (standardised) | Coefficient β | p-value |
|---|---|---|
| Investment gap | +0.84 | < 0.001 |
| Integration stress | +0.06 | 0.60 |
| Queue ratio | −0.01 | 0.91 |
| Network cost share | −0.33 | 0.005 |
| Renewable share | +0.14 | 0.16 |

### 4.5. Rankings under weight presets

Switching from the default to the reliability-first preset produces the most dramatic ranking changes in the dataset (Table 9). Under reliability-first weights (SAIDI 45%), South Africa rises from rank 10 to rank 1 and Argentina from 21 to 4, while Ireland falls from 3 to 10 and the Netherlands from 6 to 13; the Spearman correlation between the two rankings is 0.89. Conversely, the transition-first preset accentuates the crisis classification of Ireland, Australia, and Spain, while demoting South Africa and Argentina. This sensitivity, directly accessible in the dashboard, demonstrates the normative dimension of grid-health assessment and validates the concern of Sovacool et al. [28] that single-metric frameworks provide an incomplete and possibly misleading assessment.

### 4.6. What the composite reveals that the separate indicators do not

A reasonable objection to any composite is that it discards information: five interpretable indicators are compressed into one number whose meaning is harder to read. The objection has force, and the interactive dashboard is designed to meet it by exposing every dimension alongside the composite. It is therefore important to state precisely what the composite adds that inspecting the five indicators separately, or side by side on a dashboard, does not. Three things.

First, the composite supplies an ordering that no single indicator reproduces. Because integration stress and SAIDI are near-orthogonal ($\rho = 0.18$) and load on different principal components, the ranking a policymaker would obtain from SAIDI alone and the ranking obtained from the integration dimension alone are almost unrelated over the developed-world subsample; neither, on its own, identifies the set of grids that are simultaneously reliable and integration-stressed. The composite ordering is not a restatement of any one column but a genuine synthesis: the NSI correlates with its own most heavily weighted dimension (integration stress) at $\rho = 0.90$, yet the reliability-first preset re-orders the same countries to a Spearman of only 0.89 against the default, and inverts the positions of Ireland and South Africa entirely. An analyst reading five separate dials cannot see this structure without, in effect, performing the weighting in their head; the composite performs it explicitly and reproducibly.

Second, the composite is what makes the two-crisis-types finding legible as a classification rather than a pattern an expert might notice. A dashboard of separate metrics shows that Ireland has low SAIDI and high curtailment while South Africa has high SAIDI and low curtailment; it does not, by itself, tell the user that these are instances of two distinct and statistically separable stress regimes, nor which of the forty jurisdictions belong to each. The composite, together with the correlation clusters and the two-axis principal-component structure (Section 4.4), converts an observation into a testable partition: the adequacy cluster (investment gap and SAIDI) and the transition-stress cluster (integration and queue) are the statistical signature of the two crisis types, and the outcome regression (Section 4.4.5) confirms that observed outage

**Table 9**
Rank under each weight preset (selected jurisdictions; rank 1 = most stressed).

| Jurisdiction | Default | Transition-first | Reliability-first | Equal |
|---|---|---|---|---|
| Brazil | 1 | 1 | 2 | 1 |
| United Kingdom | 2 | 2 | 9 | 2 |
| Ireland | 3 | 3 | 10 | 5 |
| Australia | 4 | 4 | 7 | 8 |
| Netherlands | 6 | 8 | 13 | 10 |
| Spain | 7 | 5 | 16 | 14 |
| South Africa | 10 | 18 | 1 | 3 |
| Argentina | 21 | 26 | 4 | 12 |

duration tracks the former and not the latter. None of these results is available from the raw indicators without the integrative step the composite represents.

Third, the composite carries the normative choice on its face. A dashboard of separate metrics appears neutral but forces every user to combine the dimensions implicitly and privately whenever they reach a judgement about which grid is "more stressed." The NSI externalises that combination as an explicit, adjustable weight vector, so that the judgement can be inspected, contested, and varied, and its consequences observed through the weight presets and the Monte Carlo analysis. This is the sense in which the composite is more transparent than the separate indicators it is built from, not less: it does not hide the weighting, it makes the weighting the object of analysis. In short, the individual indicators answer "how does this grid perform on dimension X; " the composite answers "which grids face which kind of stress, and how sensitive is that judgement to the priorities we bring to it", a question the separate indicators cannot answer without being combined.

## 5. Discussion

### 5.1. Benchmarking against existing indices

The NSI is positioned alongside, not above, three established instruments. The WEC Energy Trilemma Index ranks security, equity, and sustainability; the WEF Energy Transition Index tracks transition readiness; and a SAIDI-only ranking represents the legacy reliability view. The NSI's discriminating power comes from a signal these instruments structurally cannot carry. Because integration stress is near-orthogonal to SAIDI ($\rho = 0.18$), a SAIDI-dominant ranking captures almost none of the integration signal: the reliability-first preset (a SAIDI-weighted proxy) correlates with the default ranking at only 0.89 and inverts the positions of Ireland and South Africa. The Trilemma and Transition indices, built on affordability, security, and readiness rather than operational dispatch and connection backlog, load on the adequacy/affordability axis (akin to PC2) and miss the transition-stress axis (PC1) that the NSI surfaces. The NSI's contribution is therefore not to outperform these indices on their own terms but to render visible the integration–queue stress dimension that, in the high-renewable era, has become the binding constraint for a growing set of grids.

### 5.2. The same jurisdictions under different instruments

Section 5.1 argued in general terms that the NSI carries a signal the established indices cannot. This subsection makes that concrete by tracing four jurisdictions, South Africa, Ireland, the Netherlands and Finland, through the instrument families mapped in Table 1. The four are chosen to span the space: an adequacy-crisis grid, two low-SAIDI integration-stressed grids of different kinds, and a nuclear-and-hydro-balanced system that the transition-readiness indices rank at the very top. Table 10 places each case beside how the principal instruments characterise it. The contrast is the substantive point: instruments that agree a system is well managed can nonetheless disagree about whether it is stressed, and the disagreement is informative.

South Africa repays the closest reading, because it is the case where the choice of instrument changes not merely the score but the diagnosis. The reference-period load shedding was severe on any measure: approximately 6950 cumulative hours and on the order of 16,000 GWh of energy shed in 2023, against an Eskom coal-fleet energy-availability factor of roughly 55% [41,46,47]. A distribution-reliability instrument records this as an extreme SAIDI, the derived ~4500 customer-minutes of Section 3.3.4, and stops there, offering no purchase on why the minutes accumulated. A transition-readiness composite such as the WEF ETI, by contrast, can place South Africa among the leaders in transition momentum, reflecting renewable-procurement ambition and subsidy reform, precisely while the system is shedding load, because momentum and realised adequacy are different things. Neither reading is wrong; they are answers to different questions. The NSI's contribution is to name the mechanism: South Africa scores 5/5 on the investment-gap dimension and 1/5 on integration stress, so its stress is unambiguously located in generation adequacy and network underinvestment, a state utility in technical default and a transmission build-out inadequate to the renewable pipeline, and not in the dispatch and inertia problems that define Ireland or the Netherlands. This is a structurally different form of grid insecurity, and the framework classifies it as such rather than collapsing it into a single "unreliable" label. The same logic explains why South Africa is the most weight-sensitive jurisdiction in the Monte Carlo analysis (Section 4.4.3): it sits at the point where privileging SAIDI versus integration stress moves it between rank 1 and rank 10, which is exactly the ambiguity a single-instrument view conceals.

Ireland and the Netherlands illustrate the opposite corner of the same space. Both are ranked highly by the transition-readiness composites and both report low SAIDI, yet the NSI places them among the more stressed systems, Ireland in the crisis tier, on account of integration and connection pressures that neither a reliability index nor a policy composite is built to surface: Ireland's 14% all-island wind dispatch-down and binding SNSP inertia limit, and the Netherlands' formal connection moratoriums across industrial zones. Here the instruments do not disagree about competence, they all regard these as well-run systems, but they disagree about stress, and the NSI is the one that registers it.

**Table 10**

Four jurisdictions as characterised by distribution-reliability, transition-readiness/policy composites, and the NSI. WEF ETI and WEC Trilemma entries describe each system's standing and the property that index measures; NSI entries give the default-weight tier and the binding stress. SAIDI figures are the values used in the present dataset (see Section 3.3.4 and Supplementary S1).

| Jurisdiction | SAIDI (this dataset) | Transition-readiness/ policy composites | NSI (default) | Binding stress the NSI isolates |
|---|---|---|---|---|
| South Africa | ~4500 min (derived; load-shedding-inclusive) | WEF ETI: lower quartile in absolute score but among the highest in transition momentum; WEC Trilemma: weak on security and equity | Stressed tier; NSI 57.1 | Generation-adequacy and investment-gap crisis (score 5/5); low integration stress (1/5) |
| Ireland | ~75 min | WEF ETI: upper tier, strong readiness; WEC Trilemma: strong balance grade | Crisis tier; 3rd-most stressed | Integration stress (5/5): 14% wind dispatch-down, binding synchronous-inertia (SNSP) constraint |
| Netherlands | ~23.9 min | WEF ETI: upper tier; WEC Trilemma: strong, well-balanced | Stressed tier | Connection moratoriums and congestion; integration and queue pressure invisible to SAIDI |
| Finland | ~120 min (elevated by rural distribution and storm exposure) | WEF ETI 2024: 3rd globally (Sweden, Denmark, Finland); WEC Trilemma: strong security via nuclear and hydro | Adequate tier | Low integration and adequacy stress; balancing provided by nuclear baseload, hydro and Nordic interconnection |

### 5.3. Nuclear-heavy, renewable-heavy and underinvested systems: different securities

Finland makes a useful fourth case and connects the framework to the wider grid-security debate the reviewer rightly foregrounds. Finland is ranked third in the world in the WEF Energy Transition Index for 2024, behind only Sweden and Denmark, and retains a top position in the 2025 edition; its energy-security standing rests substantially on a nuclear-and-hydro backbone, with the Olkiluoto 3 reactor entering commercial operation in 2023 and Finland becoming a net electricity exporter on a weekly basis for the first time that year [48]. In NSI terms Finland sits comfortably in the adequate tier: its integration stress is contained because dispatchable nuclear baseload, flexible hydro and strong Nordic interconnection supply the balancing services that inverter-heavy systems such as Ireland must procure explicitly, and its investment gap is modest. A nuclear-heavy system, a renewable-heavy system and an underinvested system therefore occupy three different regions of the stress space: the first is balanced but, as noted below, carries its security exposure upstream in the fuel cycle; the second is reliable yet integration-stressed; the third is adequacy-stressed. Reading them through a single instrument would flatten distinctions that matter for policy.

This nuclear-heavy case also marks a boundary of what the NSI measures, and it is worth being explicit about it. The security of a nuclear-and-hydro system such as Finland's is not fully captured by any operational network-stress dimension, because a substantial part of its exposure lies upstream, in the fuel cycle. Haneklaus et al. [14] quantify how heavily the European Union and the wider world still depend on Russian nuclear fuel-cycle services, documenting that Russia accounts for on the order of 6% of global uranium production, 20% of conversion, 46% of enrichment and 10% of fabrication capacity, that roughly one reactor in four worldwide is tied to Russian technology or supply, and that the VVER-440 fuel supply in particular is a present bottleneck, while judging Western independence achievable by around 2030 to 2035. This is a dimension of grid security, supply-chain concentration and import dependence, that is real, consequential and entirely orthogonal to the curtailment, inertia, queue, investment and outage stresses the NSI measures. The NSI does not, and is not intended to, capture it: a jurisdiction can score well on every operational dimension while carrying significant fuel-cycle exposure, and conversely. The appropriate relationship is complementarity, an operational network-stress composite such as the NSI and a fuel-cycle security assessment such as Haneklaus et al. [14] address adjacent and non-substitutable layers of the same overall question of how secure a grid is, which is why the comparative map in Table 1 lists fuel-supply-chain security among the stresses the NSI structurally omits rather than among those it subsumes.

### 5.4. Policy implications

The NSI findings carry implications at three levels of energy policy. At the system-operator level, the integration stress and queue dimensions identify where operational reform appears most pressing: Ireland's synchronous condenser needs and SNSP limit reform; Australia's system strength and transmission build-out; and Chile's central transmission corridor. These are largely network-management and infrastructure challenges rather than capacity or financing problems, and they are not highlighted by SAIDI-based assessment.

At the regulatory level, the investment-gap dimension identifies jurisdictions where tariff frameworks appear to be suppressing needed network investment: Argentina, Egypt, Indonesia, and South Africa all show strained-to-crisis investment gaps associated with below-cost-recovery pricing. Newbery et al. [29] argue that cost-reflective network tariffs, alongside appropriate capacity and balancing prices, are needed to align investment with decarbonisation and reliability; the high investment-gap scores here are consistent with the regulatory shortfalls that argument anticipates.

At the international-development level, the distinction between integration-stressed and adequacy-stressed grids bears on the allocation of climate finance: development banks and climate funds may wish to distinguish jurisdictions that need grid flexibility and connection infrastructure (the United Kingdom, Ireland, Australia, Chile) from those that need basic adequacy investment and tariff reform (South Africa, Argentina, Indonesia, Brazil). More broadly, the appropriate response depends on each system's underlying coping capacity rather than only on the measured level of stress, so the balance between flexibility, reliability, and adequacy investment will differ across jurisdictions.

### 5.5. Remarks

The NSI has several limitations that should inform its use. First, the integration stress and investment gap dimensions are scored on qualitative five-point scales, introducing subjective judgment that cannot be fully eliminated. The full scoring rubric is set out in Appendix A, together with worked examples. The scores represent a synthesis of multiple published data sources, but two analysts examining the same evidence could reach different conclusions within the 1-point band at the boundaries of each score level. The interactive weight calculator partially addresses this by allowing users to down-weight qualitative dimensions.

Second, the quality of the connection queue ratio data varies by jurisdiction. Markets with mature interconnection queue management systems (UK NESO, FERC/USA, AEMO/Australia) publish detailed, regularly updated queue statistics; markets with administrative rather than market-based connection processes (India, China) may publish aggregate figures that do not fully capture the depth of the backlog. In addition, headline queue figures substantially overstate near-term connection pressure because realisation rates are low, a caveat that the queue-ratio dimension cannot itself capture.

Third, the SAIDI normalisation ceiling of 2000 min means that differences above this threshold are not reflected in the score. For South Africa (~4500 min derived), Brazil (1200 min within ceiling), and Indonesia (800 min), this compression reduces the SAIDI dimension's discriminatory power at the high end. Users of the framework who specifically wish to compare high-SAIDI developing-world grids should consider applying alternative normalisation ceilings.

Fourth, and relatedly, the South African SAIDI value is a derived estimate rather than an officially reported figure (see Section 3.3.4) and is sensitive to the assumption used to convert cumulative national load-shedding hours into customer-minutes. Fifth, and most fundamentally, the NSI is a cross-sectional assessment based on 2023–2024 data. Grid stress is highly dynamic: South Africa's load shedding crisis, which defines its derived SAIDI, had largely abated by the second half of 2024 as Eskom's Energy Availability Factor recovered, implying a forward SAIDI substantially lower than the reference-period figure. Users should treat the NSI as a snapshot of a defined reference period rather than a structural characterisation.

### 5.6. Extensions and future work

Several extensions to the NSI framework are warranted. First, the integration stress dimension could be disaggregated into sub-dimensions: curtailment rate (objective, quantitative), redispatch cost intensity (objective, quantitative), and frequency/inertia adequacy (subjective, qualitative). This disaggregation would improve transparency and allow more precise identification of intervention priorities. Second, the investment gap dimension could be operationalised using quantitative capital expenditure ratios (actual capex as a proportion of TSO-planned capex) rather than qualitative scoring, where data permit. Third, longitudinal tracking, updating the NSI annually, and recording score trajectories would enable the kind of dynamic analysis that single-snapshot indices cannot provide and would allow the cross-sectional outcome regression of Section 4.4.5 to be extended to a predictive test against realised reliability and investment outcomes. Fourth, a sixth dimension capturing electrical energy storage adequacy could be added in future iterations, drawing on the synthesis methodology of Cebulla et al. [49], who systematise storage power- and energy-capacity requirements across more than a dozen long-horizon studies of the U.S., European, and German systems; their finding that storage power requirements rise linearly while energy requirements rise exponentially with variable renewable share suggests that storage adequacy will become an increasingly diagnostic dimension as transition-era grids move past the 50% renewable threshold.

## 6. Conclusion

This paper presents the Network Stress Index, a five-dimensional composite framework for assessing electricity network resilience

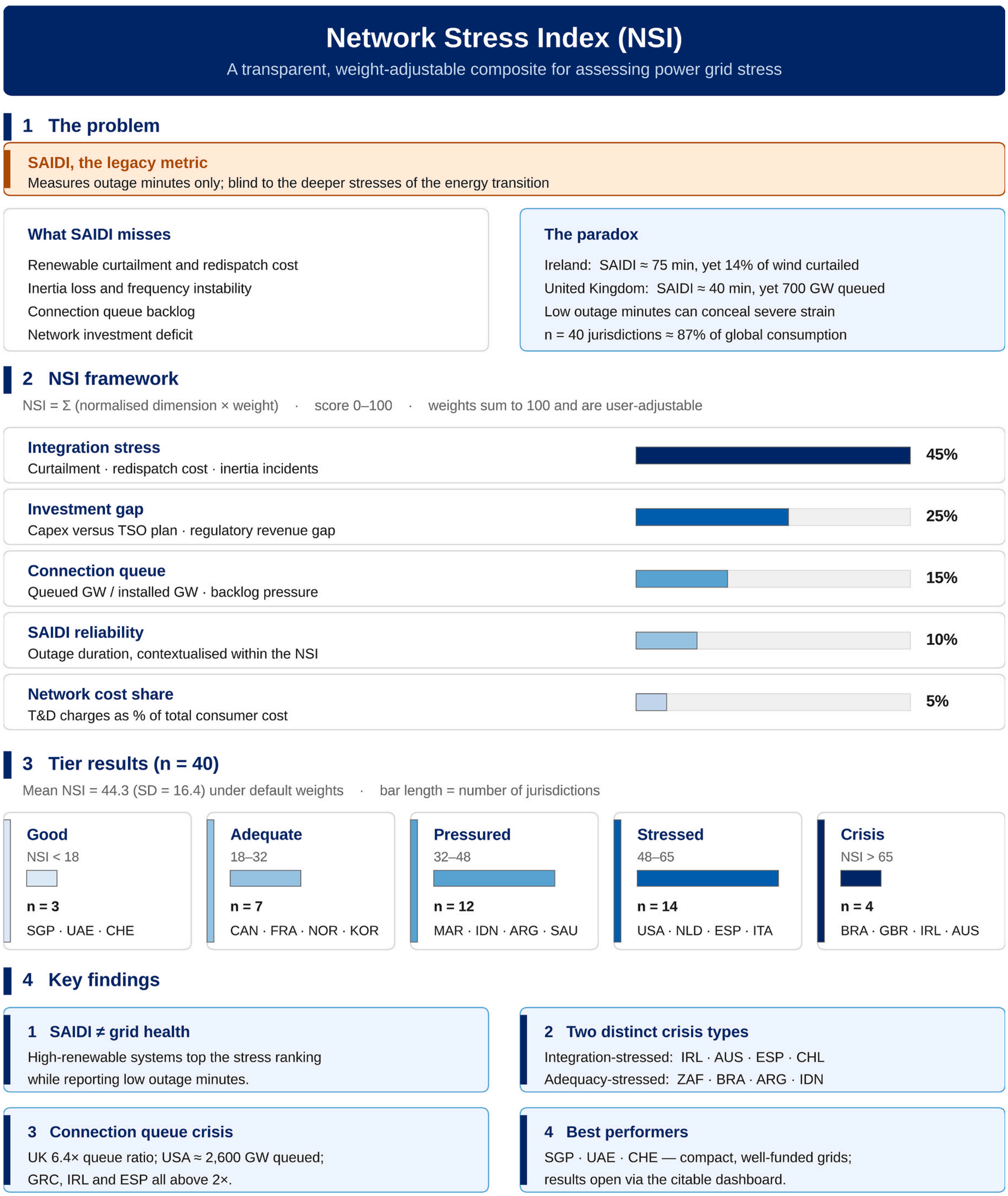


**Fig. 1.** Summary findings of the NSI framework.

across 40 jurisdictions in the context of the global energy transition. A central argument that SAIDI-dominant assessment frameworks can misrepresent the stress profile of high-renewable grids is supported by the empirical evidence from Ireland, the Netherlands, the UK, Chile, and Australia, where low outage durations coexist with severe curtailment, inertia constraints, or connection queue crises.

The NSI identifies four jurisdictions in the crisis tier (Brazil, UK, Ireland, Australia) and fourteen in the stressed tier under default weights, with the highest-performing grids concentrated in small, wealthy states with modern infrastructure (Singapore, UAE, Switzerland) or in jurisdictions where hydro-dominated generation inherently provides the balancing services that intermittent energy sources-heavy systems must procure explicitly (Norway, Canada). The most important cross-national finding is the structural distinction between integration crises of intermittent energy sources (Ireland, Australia, Spain, Chile) and generation adequacy crises (South Africa, Brazil, Argentina, Indonesia). These classifications call for categorically different policy responses.

By making the weighting function explicit and user-adjustable, the NSI embeds the methodological transparency that Bhattacharyya and Timilsina [17] and Bazilian et al. [19] identified as essential for credible analytical instruments in energy policy, and provides a research tool that is honest about the normative choices that all composite grid assessment frameworks inevitably embed. Fig. 1 summarises the findings of the NSI framework.

For completeness and to support the differentiation of investment priorities discussed above, Table 11 reports the full country ranking under the default weight configuration, reproducing the per-jurisdiction diagnostic table of the interactive dashboard [18]. Each row gives the NSI score and the underlying dimension values, the two ordinal scores with their rubric labels (Appendix A), the connection-queue ratio and the reference-period SAIDI, together with the tier assignment. The ordering makes concrete the two-crisis-types structure that the paper foregrounds: integration-stressed grids (Ireland, Australia, Spain, Chile)

**Table 11**
Full NSI country ranking under default weights (integration stress 45, investment gap 25, queue 15, SAIDI 10, cost share 5), reproduced from the interactive dashboard [18]. Integration stress and investment gap are shown with their ordinal score and rubric label; queue ratio is queued GW over installed GW; SAIDI is in minutes per customer per year for the reference period (South Africa derived, see Section 3.3.4).

| # | Country | NSI | Integ. stress | Invest. gap | Queue | SAIDI (min) | Tier |
|---|---|---|---|---|---|---|---|
| 1 | Brazil | 76.9 | 5 (Severe) | 4 (Strained) | 1.8× | 1200 | Crisis |
| 2 | United Kingdom | 68.4 | 4 (High) | 3 (Moderate) | 6.4× | 40 | Crisis |
| 3 | Ireland | 68.1 | 5 (Severe) | 3 (Moderate) | 2.3× | 75 | Crisis |
| 4 | Australia | 68.0 | 5 (Severe) | 3 (Moderate) | 1.8× | 250 | Crisis |
| 5 | United States | 64.6 | 4 (High) | 4 (Strained) | 1.9× | 367 | Stressed |
| 6 | Netherlands | 61.9 | 4 (High) | 4 (Strained) | 1.2× | 24 | Stressed |
| 7 | Spain | 61.8 | 5 (Severe) | 2 (Good) | 2.0× | 65 | Stressed |
| 8 | Chile | 60.1 | 5 (Severe) | 2 (Good) | 1.0× | 150 | Stressed |
| 9 | Germany | 57.2 | 4 (High) | 3 (Moderate) | 1.1× | 12 | Stressed |
| 10 | South Africa | 57.1 | 2 (Low) | 5 (Crisis) | 0.8× | 4500 | Stressed |
| 11 | Greece | 56.9 | 3 (Moderate) | 4 (Strained) | 3.0× | 180 | Stressed |
| 12 | India | 56.4 | 3 (Moderate) | 4 (Strained) | 1.2× | 900 | Stressed |
| 13 | New Zealand | 56.2 | 4 (High) | 3 (Moderate) | 0.9× | 150 | Stressed |
| 14 | Poland | 55.7 | 3 (Moderate) | 4 (Strained) | 1.8× | 350 | Stressed |
| 15 | Mexico | 52.8 | 3 (Moderate) | 4 (Strained) | 0.6× | 350 | Stressed |
| 16 | China | 52.5 | 4 (High) | 2 (Good) | 1.5× | 220 | Stressed |
| 17 | Italy | 49.0 | 3 (Moderate) | 3 (Moderate) | 1.5× | 160 | Stressed |
| 18 | Türkiye | 48.4 | 3 (Moderate) | 3 (Moderate) | 1.5× | 120 | Stressed |
| 19 | Morocco | 46.3 | 3 (Moderate) | 3 (Moderate) | 0.5× | 200 | Pressured |
| 20 | Indonesia | 45.9 | 2 (Low) | 4 (Strained) | 0.8× | 800 | Pressured |
| 21 | Argentina | 42.9 | 1 (Minimal) | 5 (Crisis) | 0.4× | 1100 | Pressured |
| 22 | Egypt | 42.5 | 2 (Low) | 4 (Strained) | 0.5× | 280 | Pressured |
| 23 | Saudi Arabia | 40.5 | 3 (Moderate) | 2 (Good) | 0.6× | 80 | Pressured |
| 24 | Japan | 40.1 | 3 (Moderate) | 2 (Good) | 0.2× | 16 | Pressured |
| 25 | Colombia | 38.7 | 2 (Low) | 3 (Moderate) | 0.5× | 450 | Pressured |
| 26 | Sweden | 37.2 | 2 (Low) | 3 (Moderate) | 0.7× | 140 | Pressured |
| 27 | Portugal | 32.8 | 2 (Low) | 2 (Good) | 0.9× | 85 | Pressured |
| 28 | Denmark | 32.4 | 2 (Low) | 2 (Good) | 0.8× | 25 | Pressured |
| 29 | Belgium | 32.3 | 2 (Low) | 2 (Good) | 0.6× | 22 | Pressured |
| 30 | Thailand | 32.2 | 2 (Low) | 2 (Good) | 0.5× | 120 | Pressured |
| 31 | Czech Republic | 31.9 | 2 (Low) | 2 (Good) | 0.6× | 55 | Adequate |
| 32 | Austria | 31.4 | 2 (Low) | 2 (Good) | 0.4× | 40 | Adequate |
| 33 | South Korea | 31.0 | 2 (Low) | 2 (Good) | 0.2× | 12 | Adequate |
| 34 | France | 23.7 | 1 (Minimal) | 2 (Good) | 0.8× | 60 | Adequate |
| 35 | Canada | 23.6 | 1 (Minimal) | 2 (Good) | 0.7× | 150 | Adequate |
| 36 | Finland | 22.7 | 1 (Minimal) | 2 (Good) | 0.5× | 120 | Adequate |
| 37 | Norway | 22.6 | 1 (Minimal) | 2 (Good) | 0.5× | 180 | Adequate |
| 38 | Switzerland | 17.4 | 1 (Minimal) | 1 (Excellent) | 0.3× | 14 | Good |
| 39 | United Arab Emirates | 16.3 | 1 (Minimal) | 1 (Excellent) | 0.3× | 2 | Good |
| 40 | Singapore | 15.8 | 1 (Minimal) | 1 (Excellent) | 0.0× | 2 | Good |

and adequacy-stressed grids (Brazil, South Africa, Argentina, Indonesia) are interleaved in the upper and middle ranks despite arising from structurally distinct causes, while the least-stressed tier is occupied by compact, well-funded systems and by hydro- and nuclear-balanced grids (Norway, Finland, Switzerland).

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix A. Scoring Rubric and Worked Examples

Sections 3.3.1 and 3.3.2 of the paper describe the ordinal 1–5 scales used for the integration stress and investment gap dimensions in qualitative terms. Because two of the five NSI dimensions rest on expert judgement, the credibility of the index depends on whether that judgement is exercised against transparent, observable criteria and whether independent raters applying those criteria to the same evidence arrive at similar scores. This appendix sets out the full rubric in operational detail, demonstrates its application through worked examples across six countries per dimension, and reports the result of a two-rater agreement exercise on a twelve-observation sample.

### *A.1 Rubric for the Integration Stress Dimension*

Each score level is associated with both quantitative thresholds (curtailment percentage, redispatch cost magnitude, count of stability incidents) and qualitative indicators (system operator narrative, presence of an SNSP-type constraint, role of integration in official publications). A country is placed at the level where it meets any quantitative criterion, with the qualitative indicators used to resolve cases where the quantitative criteria fall between bands. Where two quantitative criteria point to adjacent scores, the higher of the two is taken, on the principle that the rubric is intended to reflect the most binding stress dimension.

**Table A.1**
Integration stress scoring rubric.

| Score | Label | Quantitative criteria (any one is sufficient) | Qualitative indicators |
|---|---|---|---|
| **1** | **Minimal** | Curtailment of wind and solar below 1% of potential generation; redispatch/constraint costs below USD 50 million per year or below 0.5% of wholesale market turnover; no frequency or inertia stability incidents in the reference year. | Intermittent energy sources' share of generation is below 15%, or the system is hydro-rich; the system operator does not list integration as a material operational concern in its annual report; no published minimum synchronous generation requirement. |
| **2** | **Low** | Curtailment 1–3% of potential generation; redispatch costs USD 50–300 million per year or 0.5–1.5% of market turnover; isolated localised frequency events but no system-wide stability concern. | Intermittent energy sources account for 15–25%; the system operator notes integration as an emerging issue; some regional curtailment, but the national figure is moderate. |
| **3** | **Moderate** | Curtailment 3–7%; redispatch/constraint costs USD 300 million – USD 1 billion per year or 1.5–3% of market turnover; one or more documented localised stability events. | Intermittent energy sources share 25–40%; the system operator publishes a minimum synchronous generation or SNSP limit; congestion-driven curtailment in specific corridors; and first published grid-forming-inverter or synchronous-condenser procurement. |
| **4** | **High** | Curtailment 7–15%; redispatch/constraint costs USD 1–3 billion per year or 3–6% of market turnover; multiple documented near-miss stability events or one regional blackout. | Intermittent energy sources share above 35%; SNSP or equivalent limit is an active binding constraint; system operator publicly identifies integration stress as a primary operational priority; explicit dispatch-down or curtailment-rationing rules in force. |
| **5** | **Severe** | Curtailment above 15%; redispatch/constraint costs above USD 3 billion per year or above 6% of market turnover; one or more national blackouts in the reference period in which Intermittent energy sources -related operational factors were identified in the official investigation as contributing. | Intermittent energy sources share above 45% in instantaneous terms with regularity; structural dispatch failures, negative pricing for extended periods, or formal connection moratoriums in major industrial zones; integration stress is the defining narrative of the system in the reference period. |

### *A.2 Rubric for the Investment Gap Dimension*

The investment gap rubric combines three categories of evidence: realised capital expenditure against published TSO ten-year plan trajectories; the relationship between allowed regulatory revenue and operator-requested revenue in the most recent price control determination; and the qualitative reporting of investment adequacy in TSO annual reports, regulator publications, and independent reviews by the IEA, World Bank, IDB, Wood Mackenzie, and S&P Global Commodity Insights. A country is assigned to the score level at which at least one quantitative criterion is satisfied, with qualitative indicators used to resolve boundary cases.

**Table A.2**
Investment gap scoring rubric.

| Score | Label | Quantitative criteria (any one is sufficient) | Qualitative indicators |
|---|---|---|---|
| **1** | **Excellent** | Realised T&D capital expenditure equal to or exceeding the TSO ten-year-plan trajectory; regulatory allowed revenue equal to or exceeding company-requested levels in the latest price control; no published reliability deterioration trend. | TSO and the regulator both characterise investment as on track or ahead; international agency reviews (IEA, World Bank, IDB) do not flag underinvestment; no major backlog of reactive power, transformers, or substations has been reported. |
| **2** | **Good** | Realised T&D capex within 10% of TSO plan; allowed revenue within 10% of company request; reliability trend stable. | TSO and regulator characterise investment as broadly adequate but acknowledge specific gaps; one or two corridor projects are delayed but not strategically critical. |
| **3** | **Moderate** | Realised T&D capex 10–25% below plan; or allowed revenue 10–25% below request; or reliability indicators show modest deterioration over three years. | Independent reviews (IEA country review, Wood Mackenzie, S&P) identify investment gaps as material; TSO publishes a backlog of strategically important deferred projects; the tariff framework is under review. |

(*continued on next page*)

**Table A.2** (*continued*)

| Score | Label | Quantitative criteria (any one is sufficient) | Qualitative indicators |
|---|---|---|---|
| 4 | **Strained** | Realised T&D capex 25–50% below plan; or sustained shortfall in allowed revenue versus need; or reliability indicators show clear multi-year deterioration; or T&D operator carrying debt levels that constrain capex. | International agencies explicitly flag underinvestment; transmission operators have formally warned of capacity-limited connection refusals; tariff suppression by political process is documented in regulator reports; and major project deferrals affect strategic corridors. |
| 5 | **Crisis** | Realised T&D capex more than 50% below plan; or state utility insolvency or technical default; or load shedding driven by transmission or distribution failure rather than generation shortfall. | Chronic structural underinvestment recognised across regulator, TSO, government, and international agency sources; system in active or recent crisis attributable in material part to network underinvestment; capex programme insufficient even to maintain existing asset base, let alone meet transition demand. |

### *A.3 Worked Examples*

To demonstrate how the rubrics translate into scores for individual countries, 12 worked examples are presented in Table A.3: 6 for integration stress and 6 for investment gap. The countries are deliberately chosen to span the full ordinal range and to include cases at the boundaries between score levels, where the rubric must do real work. Each row records the score awarded and the specific evidence applied to the rubric criteria.

**Table A.3**
Worked example scores for twelve country–dimension pairs, with the evidence applied to the rubric criteria.

| Country | Dimension | Score | Evidence applied to rubric criteria |
|---|---|---|---|
| **UAE** | Integration stress | 1 | Intermittent energy sources accounted for less than 15% in 2024 (predominantly gas-fired generation, with growing solar). TAQA/EWEC system operator annual reporting does not identify integration as a material operational concern: no published curtailment data, no SNSP limit, no stability incidents. Score 1 (minimal) satisfied on both quantitative (no measurable curtailment) and qualitative criteria (no integration narrative). |
| **USA** | Integration stress | 3 | Intermittent energy sources accounted for approximately 17% of total energy nationally in 2024, with very wide regional variation. ERCOT curtailment around 5% of wind; CAISO around 3% of solar (CAISO 2024 annual report). Redispatch and congestion costs over USD 1 billion nationally, spread across multiple RTOs and documented localised stability events, but no national-scale incident. Score 3 (moderate), curtailment in the 3–7% band in the largest Intermittent energy sources markets and congestion costs in the moderate band. |
| **Germany** | Integration stress | 4 | Renewable curtailment of 3.5% of renewable generation in 2024 [35]. Total grid congestion management costs approximately EUR 2.8 billion (USD 3 billion), in the high band on absolute terms but moderate as a share of market turnover; multiple documented redispatch interventions across the north–south corridor. Score 4 (high) is driven primarily by the absolute cost magnitude and the operational prominence of redispatch in TSO reporting; the alternative, score 3, was considered. |
| **Ireland** | Integration stress | 5 | 14% all-island wind dispatch-down in 2024, of which 96% is attributable to the minimum synchronous generation constraint [5]. SNSP limit is the operationally defining constraint of the system. Intermittent energy sources share regularly above 45% instantaneously. EirGrid explicitly characterises integration as the primary operational priority. Score 5 (severe) on multiple criteria: curtailment in the >15% band when measured against available wind, SNSP is a binding constraint, and integration is the system narrative. |
| **Spain** | Integration stress | 5 | April 2025 Iberian blackout in the reference period ([26]; ENTSO-E 2025), in which official investigations identified voltage-control adequacy under high penetration of intermittent energy sources as a contributing factor in a complex chain. Wind and solar at approximately 45% of 2024 generation, with regular periods of >70% instantaneous Intermittent energy sources. Score 5 (severe) on the blackout criterion. |
| **Australia** | Integration stress | 5 | 7.2 TWh was curtailed in the National Electricity Market in 2024, a 67% year-on-year increase [36]. Intermittent energy sources accounted for more than 40% of NEM generation during the reference period. Documented system-strength shortfalls and explicit AEMO procurement of synthetic inertia. Score 5 (severe) on curtailment trend and structural system-strength procurement. |
| **Switzerland** | Investment gap | 1 | Swissgrid 2024–2040 strategic grid plan executing on or ahead of schedule; ElCom tariff framework cost-reflective; no reliability deterioration trend. International reviews characterise Swiss network investment as broadly exemplary; Score 1 (excellent). |
| **Germany** | Investment gap | 3 | Realised transmission build-out is materially behind the TSO ten-year network development plan, particularly on the north–south HVDC corridors (SuedLink, SuedOstLink). Bundesnetzagentur acknowledges delays as material. Allowed revenue regime in active reform. Score 3 (moderate): gaps are real and well-documented, but the capex programme remains large, and reliability has not yet deteriorated. |
| **USA** | Investment gap | 4 | The transmission build-out is widely recognised as inadequate to accommodate the LBNL-documented interconnection queue. FERC Order 1920 (2024) was introduced for exactly this reason. Institutional fragmentation across RTOs and state regulators slows project delivery. Score 4 (strained) on the systemic inadequacy of transmission relative to need, despite absolute capex being large. |
| **Indonesia** | Investment gap | 4 | PLN is structurally constrained by retail tariff suppression; allowed revenue is chronically below cost-reflective levels; the T&D investment programme is periodically deferred. World Bank and IEA country reviews flag underinvestment as a material issue. Reliability indicators show deterioration in eastern provinces. Score 4 (strained). |
| **Argentina** | Investment gap | 5 | Distribution operators (Edenor, Edesur) operated for years under frozen tariffs, producing revenue below maintenance costs; ENRE has documented sustained underinvestment; SAIDI in the 1000-min range, driven by distribution-asset condition rather than generation shortfall. Score 5 (crisis) on the tariff-suppression and reliability-attribution criteria. |
| **South Africa** | Investment gap | 5 | Eskom repeatedly entered technical default during the reference period; the operator and the National Treasury publicly acknowledge the transmission build-out as inadequate to enable the published renewable procurement programme; structural underinvestment is recognised across regulator, government, and international agency sources. Score 5 (crisis). |

### *A.4 Inter-rater Reliability*

Because two of the five dimensions rest on expert judgement, a second rater independently re-applied the published rubrics (Tables A.1 and A.2) to the documented evidence for the twelve worked-example jurisdictions of Table A.3. The exercise tests rubric reproducibility, whether the documented criteria, applied to the documented evidence, regenerate the published scores. Agreement was high (Table A.4): exact agreement 91.7% (11 of 12), agreement within one band 100%, linear-weighted Cohen's $\kappa = 0.94$, and quadratic-weighted $\kappa = 0.98$. The sole discrepancy (Ireland integration stress, scored 5 by the first rater and 4 by the second) falls precisely on the band-4/5 boundary that the rubric flags, since 14% dispatch-down measured against available wind brushes the 15% threshold. The scoring instrument is provided in Supplementary S3 to enable a fully blinded third-party exercise prior to publication.

**Table A.4**
Inter-rater agreement on the twelve worked-example jurisdiction–dimension pairs.

| Agreement statistic | Value |
|---|---|
| Exact agreement | 91.7% (11/12) |
| Agreement within one band | 100% |
| Linear-weighted Cohen's κ | 0.94 |
| Quadratic-weighted Cohen's κ | 0.98 |
| Sole discrepancy | Ireland integration stress (5 vs 4), documented boundary case |

## Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2026.102337.

## Data availability

Data will be made available on request.

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